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THE BENDING OF WOOD

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Wood bending is practiced in the production of a large variety of products ranging in size from embroidery hoops to large ship parts and including such varied items as barrel hoops and staves, handles for shovels, forks and other tools, wheel rims, automobile parts, tennis racquets, snow shoes, hockey sticks, toboggans, skiis, snaths, walking sticks, umbrella handles, and canoe and boat parts.

In general the hardwood species are more readily softened by the action of heat and moisture and are more suitable than conifers in bends involving large deformation. Also in many bent parts hardwoods are desired for the appearance or other characteristics. Consequently, hardwoods contribute most of the wood used for bending. The elms, ashes, and hickories are preferred for bendings in which extreme deformation must be produced. Oaks, beech, birches, maples, and red gum are largely used in furniture construction.

Selection of Stock

Wood for bendings involving extreme deformation must be straight grained and free from defects. In pieces involving only moderate deformation irregularities of grain direction and small knots may be permitted on the tension side of the piece provided efficient straps are used. Knots or other defects that would interfere with uniform shortening are undesirable on the compression side.

In all species there is considerable variation in the quality of clear wood and a range in such properties as weight, hardness, and strength. The heavier stock in any species is ordinarily the harder and stronger and hence the more serviceable in bent articles in which these properties are desirable. No information is available to show definitely what quality of wood can be most successfully bent. In hickory the most flexible material is apparently that from near the base of the tree and the same is probably true of other species except that wood from near

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the base of swamp grown hardwood trees is often low in density and in strength properties.

Steam Bending

The principle of steam bending is that the wood is rendered flexible by the application of heat and moisture and while in this condition is bent to the desired shape, and so held until, through the hardening and stiffening that results from drying the wood, the shape becomes fixed.

Wood may be stretched only a small amount (about 1 percent of its length) without tension rupture. The shortening or upset that can be brought about, however, is much greater. Wet or moist wood can be compressed with less force and to a greater degree without disfigurement than dry wood. Heat applied to wet wood further reduces the resistance to compression and increases the possible shortening. Heat and moisture, however, do not greatly increase the attainable stretch. In any instance, therefore, in which the difference in length between convex and concave faces of a bent piece amounts to several percent the major portion of the deformation must be produced by shortening. Hence the desideratum in selecting and preparing stock and in the bending manipulation is to produce this shortening in proportion to the thickness and curvature of the piece at each point along the length.

The difference in length between the convex and concave faces of a bend is equal to the relative curvature expressed as the ratio of thickness (in the direction of the radius) to the radius of the convex face. Thus for a piece 3 inches thick bent on a form of 17-inch radius the outer radius is 20 inches and the deformation or relative curvature is $3/20 = 0.15$ or 15 percent. Many bent parts entail relative curvature as high as 10 to 12 percent and occasional parts of small cross section are bent to a relative curvature as high as 30 percent. The same relative curvature is more readily attainable with thin members than with thicker ones. One possible reason is that brief steaming softens thin stock throughout whereas in the longer time required for heat and moisture to penetrate thicker stock the surface becomes "over cooked."

In the bending of pieces whose thickness (in the direction of the radius) is large compared to their width there is a tendency for lateral or sidewise buckling to occur. With pieces whose depth is as much as twice their width, lateral support should be provided to restrain sidewise buckling.

Cutting the piece as nearly as possible to the finished depth before bending decreases the danger of objectionable wrinkles. If the stock is left over-size such wrinkles may be caused by the extra depth and may not be removed in finishing.

Saw marks and other irregularities tend to localize the upset, hence surfacing before bending is advantageous. Experience has shown that bending is more successful if the curved surfaces are plain sawed than if they are quarter sawed. Defects, such as knots and local irregularities of grain, are less detrimental to bending if on the convex than if on the concave side of the bend.

Seasoning and Softening

Although one of the most important considerations in connection with the steam bending of wood is its moisture content, no adequate scientific study has been given to this phase. Theoretically the ideal condition for maximum softening is that the moisture content throughout the piece be just sufficient to fully saturate all the fibers. Moisture in excess of this presumably will not produce any greater softening, but probably is not detrimental, except that it adds to the water to be removed in drying, unless there is so much that the cell cavities are nearly or completely filled, in which case sufficient hydraulic pressure may be produced in these cavities as they are deformed in bending to cause disruption of the structure.

Stock in all degrees of seasoning from thoroughly green to thoroughly air dried or even kiln dried to a moisture content below that attainable by air drying is used. Green stock has the advantage of absence of checks, which are an obstacle to uniform upset. However, moisture that may be present in excess of that needed for softening lengthens the time required for drying and fixing the bends. Many bent parts are made successfully from thoroughly air-dried stock and provided the stock is not checked this is probably the best moisture condition. Stock that has been well air dried can be subjected to much more drastic drying conditions without checking and honeycombing than can green stock. Hence, it can be dried more rapidly after bending. The chief obstacle to the bending of material that has been dried to a low moisture content is the difficulty of introducing into it sufficient moisture to produce the necessary flexibility.

The usual softening agents are steam and hot or boiling water. Hot water is frequently used when a bend is to be made near one end of a piece, in which case only the portion to be bent is immersed. Steam must be wet or at least fully saturated in order to prevent surface drying of green stock and to add moisture to dry stock. Steaming is commonly done with exhaust steam or with live steam blown through water into a box or chamber that is not sufficiently tight to sustain pressure. Steam under pressure up to about 35 pounds per square inch gauge as a maximum is sometimes used to heat the stock more quickly and to a higher temperature. Opinions differ as to the comparative merits of hot water soaking, pressure and nonpressure steaming.

A common rule of thumb in the use of steam at atmospheric pressure is to steam for 1 hour per inch of thickness. Obviously, however, the length of the steaming period needs to be varied according to the species and moisture content of the stock and the severity of the bend. The ideal condition for maximum flexibility, that is, thorough saturation of the wood fibers without excess moisture in the cell cavities is very difficult if not impossible to attain. The maximum attainable flexibility, however, is probably not needed except for bends of extreme curvature.

In any bend that involves more than about 2 percent deformation, the neutral surface or surface along which the wood fibers are either elongated or compressed must be moved toward the tension face. For example, in a bend involving 10 percent deformation only 1/10 of the total can occur as stretch leaving 9 percent to be accomplished as upset. In such an instance the neutral surface can be not more than 1/10 of the depth from the tension face. When the wood is well softened the tensile strength sufficiently exceeds the compressive resistance to bring the neutral surface to as near as 1/3 or 1/4 the depth from the tension face. Hence, if the grain is perfectly straight so that bending does not induce stress in tension across the grain, bends involving up to 3 or 4 percent deformation can be accomplished without tension failure. For more severe bends the tensile strength of the wood is ordinarily insufficient of itself and must be supplemented by metal straps or bands to afford a total tension that will balance the resistance of the part of the piece that must be compressed.

Substantial end blocks or bulkheads must be securely attached to the straps in order to convert the tension into pressure against the ends of the bending blank. Short bulkheads as illustrated in Figure 1, A, are unstable and will tip under the action of the bending forces as illustrated in Figure 1, B. Such bulkheads exert slight pressure only on one edge of the end of the stock and are therefore quite ineffective in restraining stretch.

Figure 2 represents a stick in the process of being bent. Successful bending requires that upset take place at O, the last point of contact between stick and form, and that crushing at the end of the stick be avoided. Also because heat and moisture penetrate more readily longitudinally than across the grain, the end of a steamed piece is likely to be softer than the body of the piece. Hence, it is necessary that the unit compressive stress be less at the end of the stick than at point O. This can be assured by applying the resultant end pressure, p^1, at the mid height of the piece. In order to prevent the occurrence of any stretch and crushing at the end of the piece shown in Figure 2, X, which is the distance from the bending force P to the pivot near the end of the stick, must be about three times as great as L, the distance from the end of the piece to the last point of contact with the form. Hence, X must decrease as L decreases with the progress of the bending. Furthermore the resisting moment of the piece remains practically constant and

must be balanced by the external bending moment P (X + L). Accordingly, as bending progresses the force P must increase and its point of application must move closer to the end of the piece being bent.

This analysis explains why bending apparatus arranged as in Figure 2 is frequently inadequate, since it is seldom convenient or possible to provide long enough bulkheads or to shift the point of application of forces during the operation. However, apparatus that only approximately fulfills these requirements often functions satisfactorily. Frequently, however, bulkheads are so short that they are quite ineffective and a large percentage of failures occurs through their use. Although friction between strap and stick has been disregarded in the foregoing analysis it may be sufficiently great to assist in providing end pressure and preventing tension failures. Any apparatus that permits even occasional tension failures should be regarded as inadequate.

Tension failures are often attributed to improper seasoning or insufficient softening of stock when in reality they are due to insufficient end pressure. A simple scheme for providing automatic regulation of end pressure is illustrated in Figure 3. Here the leverage for the bending force P is afforded by a "reversed lever" extending back along the piece from its end. The pressing of the reversed lever against the piece affords resistance to the tipping of bulkheads previously mentioned. The bending force P can be applied at any point beyond the last contact of the stick with the form. If the lever arm about the point of contact is made very short, however, the force will necessarily be large, and undesirable crushing of the bending stock against the form may result. This principle of the reversed lever is embodied in a common type of double arm bender used for bending wheel rim and other semicircular parts and in a similar single arm type of machine. Some of these machines also have devices for automatically releasing some of the end pressure as bending progresses thus allowing some stretch of the wood to take place.

Straps stretch with repeated use and furthermore it is difficult to cut bending blanks to exactly fit a strap of fixed length. If blanks are too short they may stretch before any end pressure from the bulkhead is obtained. If too long, forcing them into place will cause crushing at the corners of the end, and this may so weaken them at that point that point that the upset will be localized there instead of taking place where it should. In either case tension failures are likely to result. Consequently, some means of adapting the length of the strap to the length of the bending blank is needed. This can be accomplished by screws threaded through the bulkheads and bearing against the plates used to distribute the end pressure over the ends of the piece. These screws can be released as bending progresses if it is desired to reduce the force required to accomplish the bending by permitting as much stretch as can be allowed.

Forms

Three kinds of forms are used in wood bending: (1) simple wood, metal, or metal covered wood of the proper shape to fit the concave side of the bend; (2) hollow steam-heated metal forms on which the bends remain until the shape is fixed by drying the wood; (3) hydraulic presses having hollow steam-heated platens so shaped that the bending blanks can be pressed to the desired form in the openings between successive platens.

Bends made on or between heated forms are left in place until they are dried sufficiently to retain their shape approximately. Bends made on unheated forms are ordinarily dried in a kiln either on the bending forms or after transfer to drying forms or to retaining clamps. Principles that govern the drying of straight stock are applicable in the drying of bent wood. Extreme care needs be exercised in the steaming of bent wood during the drying process in order to avoid tension failures. If the bends have been made from air dried stock somewhat severer drying schedules may be used than can be applied in drying stock from the green condition. The use of hot forms or hot presses with green stock is inadvisable as honeycombing and severe checking is likely to be caused by the severe drying conditions.

Special Bending Methods

Chemical treatment of wood to soften it for bending is frequently proposed. The Forest Products Laboratory has not investigated the possibilities of chemical softening for bending and knows of no authoritative information on the subject. It seems probable, however, that chemical action sufficient to render wood more flexible and plastic than can be done by ordinary methods of steaming might render it unsuitable for uses in which strength is important.

A comparatively recent departure from customary practice in wood bending is represented by a machine that utilizes three rolls triangularly arranged and with adjustment provided so that the spacing can be adapted to the thickness of the wood and the radius of bend desired. The rolls are hollow and are heated by interior gas flames. A spring-steel strap is fed through with the bending stock and next to its convex face. This strap has no bulkheads and the only restraint of extension of the wood comes from friction with the strap. This machine is reported to operate successfully on dry (presumably air dry) wood up to 7/8 inch in thickness. The process is also applied to the bending of plywood. Another recent development is a German patent for the preparation of flexible wood through the application to hot moist wood of heavy pressure to compress and upset it longitudinally. The claim is that this material can be produced and dried "in the straight" and can later be soaked and bent, following which it is fixed to the desired shape by drying

Characteristics of Bent Wood

Wood that has been steam bent and dried while held to shape tends to bend further with additional drying or to straighten with the absorption of moisture. This suggests that drying on the forms, or while the wood is otherwise held to the desired shape should be to approximately the moisture content the wood will have in service.

If a large amount of moisture is absorbed while a piece of bent wood is held against straightening, the tendency of the concave side to swell may produce sufficient stress to cause tension failure at the convex face, hence the need for caution in steaming of such wood during the drying process.

Inasmuch as in many bends the deformation is far beyond the proportional limit and well beyond the deformation at maximum stress, it is not to be expected that the strength of such parts will be so great as that of wood that has not been subjected to the bending process. Results of only a few tests of bent wood are available.

White ash sticks 1-1/4 inches square steam bent to a radius of about 180 inches and tested in static and impact bending with the concave side in tension, developed practically the same strength values as control pieces that had not been steamed or bent. Similar steam bent Sitka spruce sticks developed nearly the stress for normal wood in static bending but were broken with much smaller impact shocks than normal wood. Failures were by tension through visible compression failures that had been induced in bending.

Static bending tests of white oak and Douglas fir barrel staves placed with the convex faces in tension developed modulus of rupture values of 70 to 85 percent of those for normal wood.

In tests of a 2-3/4 inch square wheel rim that had been steam bent on a form of about 49-inch diameter, a full section developed a modulus of rupture of 8,000 pounds per square inch. Another piece of the same rim was hand sawed to yield two pieces each approximately one-half the depth of the original section. Tests of these gave modulus of rupture values of 12,400 and 7,300 pounds per square inch for pieces from the outer and inner halves, respectively, of the original piece. Specimens from this rim were all tested with the concave face in tension.

Although these tests are only fragmentary they confirm the expectation that the wood will be reduced in strength in accordance with the amount of deformation that has been produced in bending. Excellent service given by steam bent parts indicates that the lowered strength values do not destroy the usefulness of such parts.

Laminating

Laminated bent members are formed by assembling a number of comparatively thin slices or laminae of wood with glue on their adjacent faces to the desired total thickness after which the assembly is bent to the desired shape and so held until the glue has set. Or, previously steam bent laminae may be similarly assembled with glue and clamped to forms of the desired shape until the glue sets as is sometimes done in making tennis racquet frames. One of the principal advantages, however, of laminating is that laminae may be made sufficiently thin that they can be bent without the use of steam or other softening agents. Another advantage is that wood selected for its appearance can be used for face laminae and cheaper material for others.

Tests have shown that air-dry coniferous woods in thicknesses of 1/2 inch and 3/4 inch can be bent to a radius as small as 80 times the thickness without the application of heat or moisture other than that supplied by ordinary animal glue. Although bending to such a radius stresses the material approximately to its ultimate strength, tests on specimens made of 4 such laminae have shown that the strengths at proportional limit and the ultimate strengths in bending and in compression parallel to grain are not more than about 20 percent below that of straight wooden pieces and the stiffness not more than about 10 percent deficient. When the laminae are bent to a radius of 160 times their thickness the deficiencies in these properties are approximately one-half as great; when the radius is as much as 320 times the thickness the deficiencies in strength properties are very small.

Bending to a radius of about 80 times the thickness is about as severe as can be done with material 1/2 inch to 3/4 inch thick and practically free from defects. Thinner material can probably be bent somewhat more sharply. Knots or cross grain will greatly reduce the curvature that can be produced without breakage. In producing members of a given curvature it is obviously desirable to have the laminae as thin as is otherwise economical in order to reduce the danger of breakage, increase the strength of the member, and lessen the force required to form the band.

The stress induced in the individual laminae in bending has a tendency to cause the member to straighten. It would be expected, however, that the greater the number of laminae the less straightening would occur. This is confirmed by observations on members composed of from 2 to 12 laminae which show that straightening diminishes rapidly with increase in the number of laminae. With six or more 1/2-inch laminae bent to a radius of 80 inches, release from the form after the glue had set resulted in practically no change of form and there was little subsequent change with such fluctuations in atmospheric humidity as produce quite noticeable changes in steam bent members.

Curved parts commonly made by laminating include rims of grand pianos and rims for tables having tops of circular, oval, or other curved outlines. Seemingly there is a field for expansion in the use of curved parts produced by laminating.

Members that meet at an angle, such as the side posts and top bows of an automobile body, could be replaced by a continuous laminated piece. Or in such an instance "fingers" cut on the end of one member could be interlaced with similar fingers on the end of the other and the assembly bent and glued to a curve of small radius.

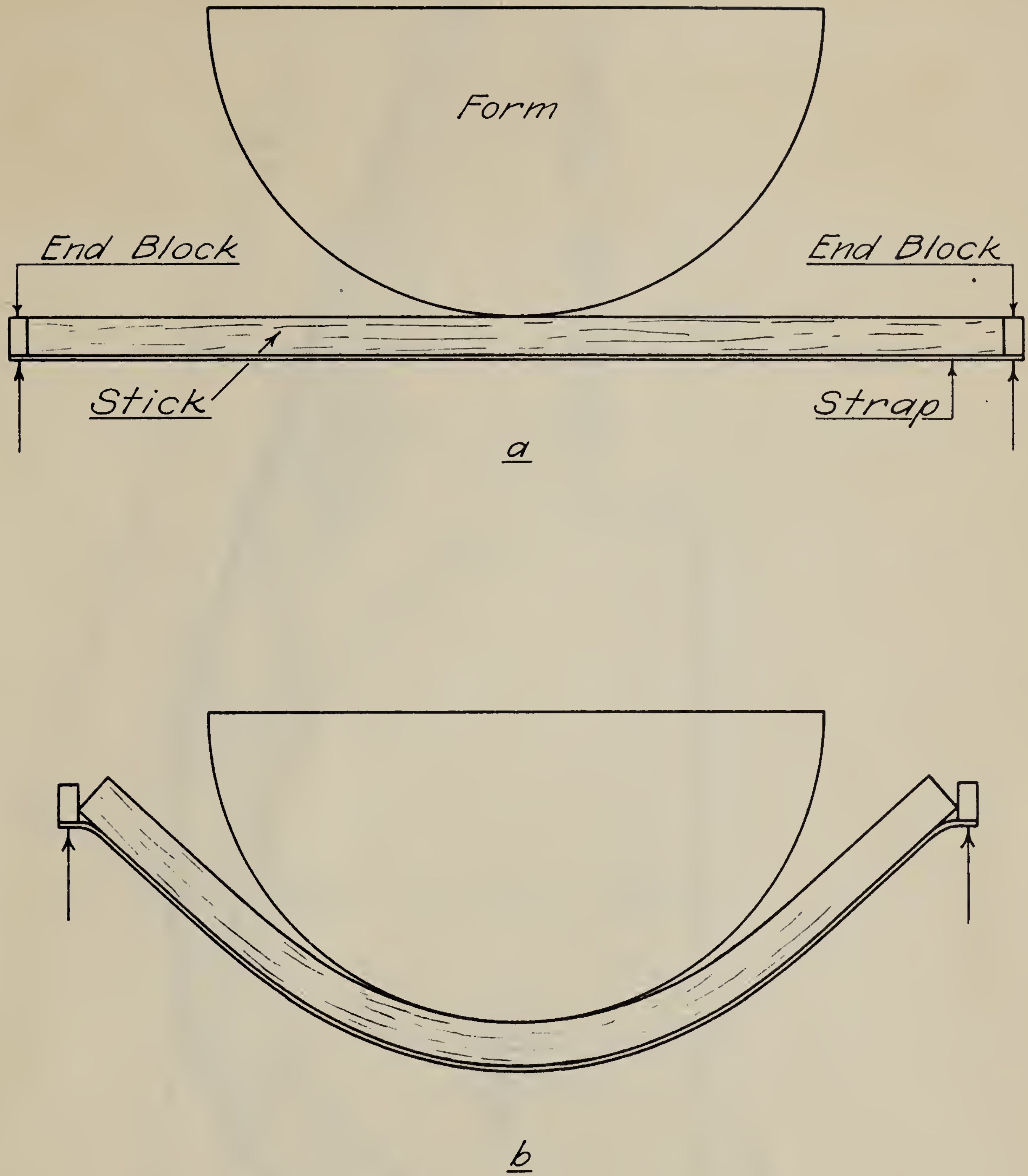

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Figure 1.--Sketch of a bending strap having ineffective end blocks: (a) before pressure is applied; (b) after pressure is applied. Note how end blocks tip over and slip off.

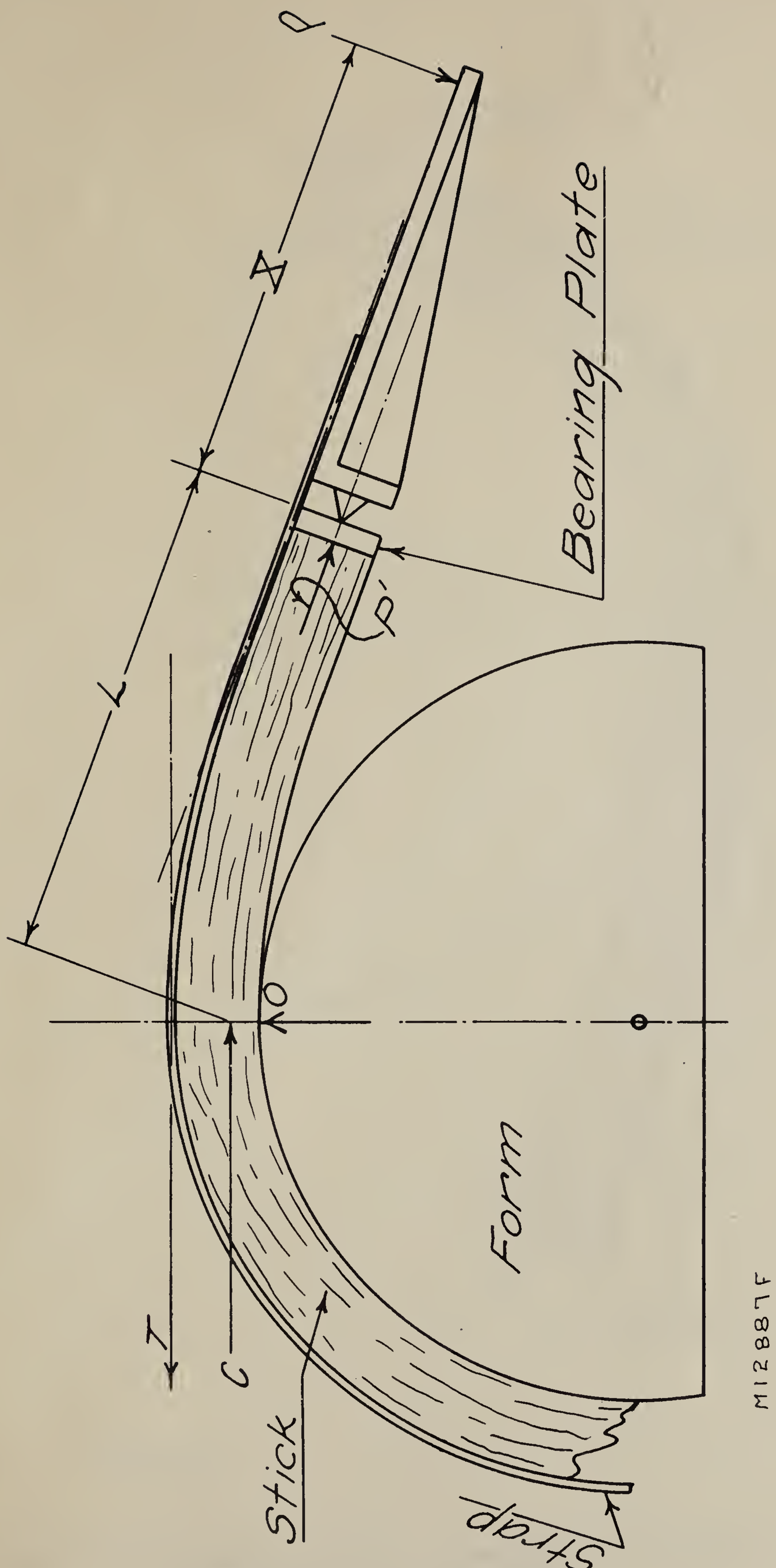

Figure 2.--Sketch of a stick in process of being bent.

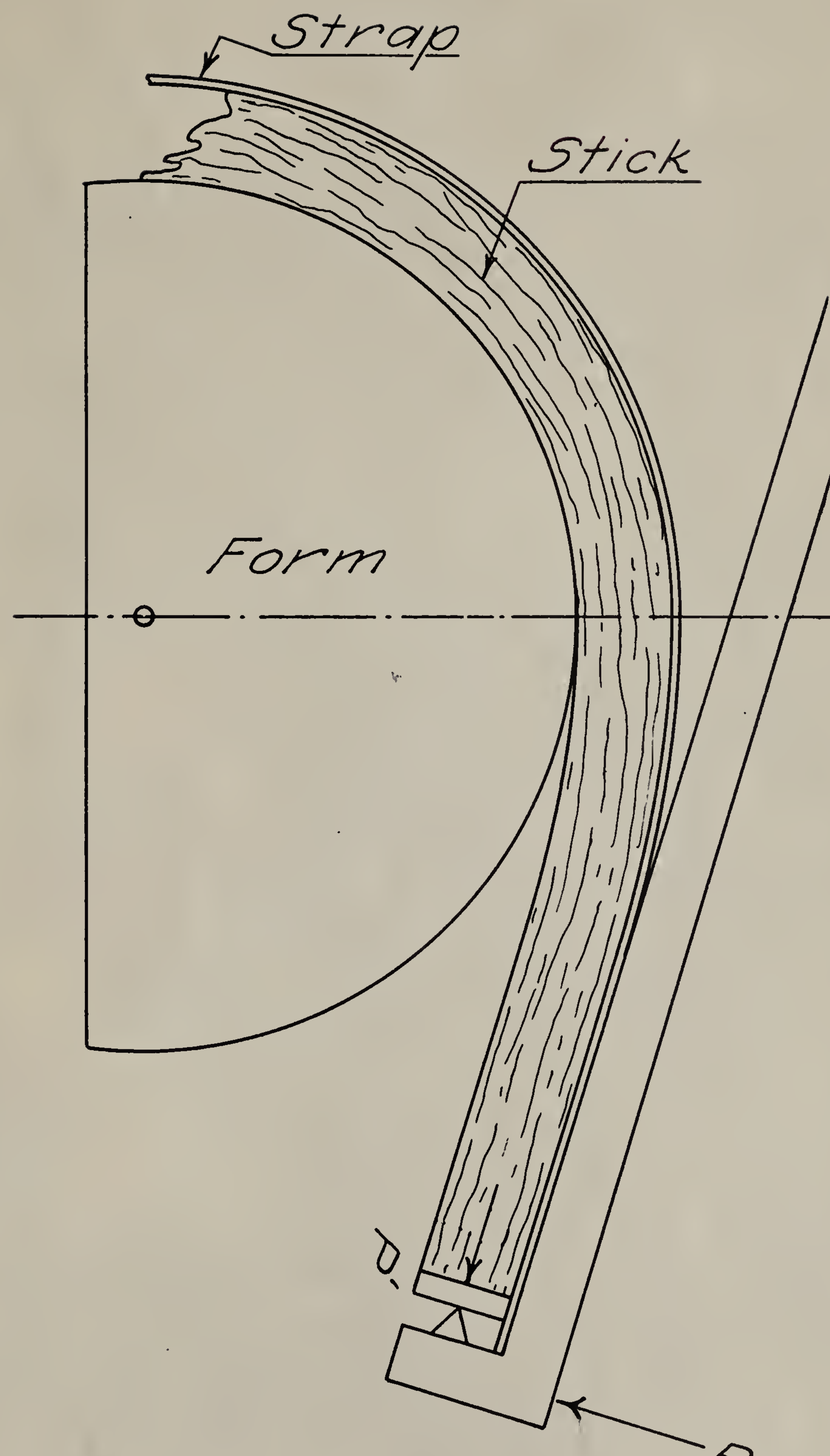

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Figure 3.--A simple method of providing for automatic regulation of end pressure.